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Evaluating the Seismic Performance of Low-Rise Concrete Buildings Using Nonlinear Static Analysis

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Abstract Linear force-based analysis is the conventional method for seismic design in building codes, but it has limitations in accurately predicting the seismic behaviour of buildings, especially during strong earthquakes. While nonlinear time history analysis (NTHA) is theoretically more accurate, it is limited by high computational costs and the challenge of selecting appropriate ground motion records. Nonlinear static pushover analysis (NSPA) has become a popular and simpler alternative for evaluating building performance during earthquakes, but it lacks a rigorous theoretical foundation and does not account for dynamic effects. This study aims to investigate the accuracy of NSPA in predicting the seismic behaviour of low-rise concrete buildings with 3 and 5 storeys located in a high seismic hazard zone in Indonesia. The research focuses on addressing the limitations of current methods for seismic design and evaluation of low-rise concrete buildings and aims to compare the accuracy of NSPA and NTHA in predicting the global and local responses of the buildings. Commercial finite element software is used to perform pushover analysis considering both geometric and material nonlinearity. The study's findings demonstrate that pushover analysis is slightly less conservative than NTHA in predicting the seismic response of low-rise concrete buildings. The research provides insights into the use of pushover analysis as an effective and simplified method for seismic evaluation and design of low-rise concrete buildings, while also highlighting the importance of understanding the limitations and accuracy of the method. These findings can be used to improve the seismic design of low-rise concrete buildings and enhance their safety during seismic events.

Keywords Nonlinear Analysis, Pushover, Concrete Building, Earthquake

1. Introduction

Indonesia is located in a moderate to high seismic zone and has experienced numerous destructive earthquakes that have caused significant loss of life and property damage. The most recent example was the 2018 Sulawesi earthquake, which resulted in more than 4,300 fatalities and widespread destruction of buildings and infrastructure [1]. To mitigate the impacts of earthquakes, it is necessary to design building structures that are resilient and able to withstand seismic forces.

However, the current seismic design regulation in Indonesia is based on a linear force-based analysis method, which has limitations when it comes to accurately predicting the nonlinear behaviour of building structures under strong earthquake loads. To address this limitation, recent researches have focused on two nonlinear analysis methods: nonlinear static pushover analysis (NSPA) and nonlinear time history analysis (NTHA) [2]–[4].

While NTHA is theoretically more accurate, its practical application is limited due to its high computational cost and the challenge of selecting appropriate ground motion records. On the other hand, NSPA is a simpler and more widely used tool for predicting seismic response demand and identifying weak structural elements in building structures [5]–[8]. However, NSPA is an approximation method that lacks a rigorous theoretical foundation and does not account for dynamic effects.

While NSPA is a simpler and more widely used tool for predicting seismic response demand, it lacks a rigorous theoretical foundation and does not account for dynamic effects. Therefore, a research gap could be to investigate how the accuracy of NSPA can be improved to better account for dynamic effects and provide more accurate predictions of seismic behaviour in building structures. By doing so, the accuracy of NSPA as a tool for predicting seismic behaviour in building structures can be assessed, and areas where further research is needed to improve the precision of current design methods can be identified.

2. Literature Review

Seismic design is an important consideration for building structures in regions prone to earthquakes. The goal of seismic design is to ensure that building structures are resilient and able to withstand the forces exerted by earthquakes. In Indonesia, the current seismic design regulation is based on a linear force-based analysis method, which is relatively simple to apply, but has limitations when it comes to accurately predicting the nonlinear behaviour of building structures under strong earthquake loads [9].

Nonlinear analysis methods have been proposed as a way to improve the accuracy of seismic design for building structures. Two of the most commonly used nonlinear analysis methods are nonlinear static pushover analysis (NSPA) and nonlinear time history analysis (NTHA) [10].

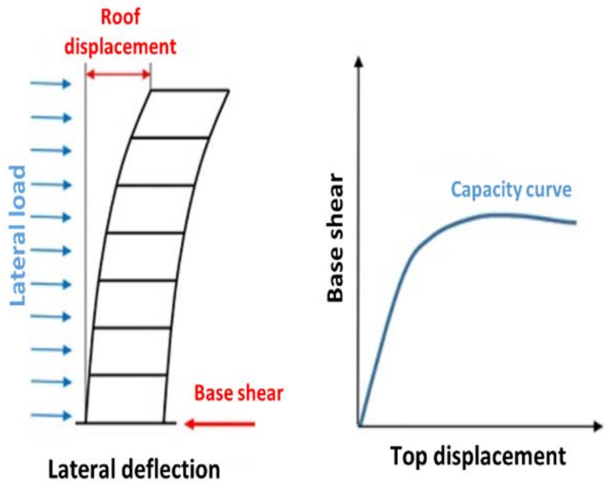


Figure 1. Illustration of NSPA

NSPA is generally a static nonlinear analysis performed to obtain a force-displacement curve which represents the global behaviour of the structures against lateral loads. In NSPA, the structure is subjected to a specific lateral load pattern as illustrated in Figure 1. The load magnitude incrementally increases until the structure collapse or reaches a target displacement. The target displacement expresses the lateral drift of the building subjected to the design earthquake [11].

NSPA is a simplified method for predicting the response of building structures to seismic loads. The method assumes that the response of the structure can be related to the response of an equivalent single degree-of-freedom (SDOF) system and is therefore limited in its ability to capture the full complexity of nonlinear structural behaviour [12].

In contrast, NTHA is a more accurate and comprehensive method for analysing the nonlinear behaviour of building structures under seismic loads. NTHA involves the application of ground motion records to a detailed finite element model of the building structure and allows for the simulation of the dynamic response of the structure to seismic loads. Although NTHA is more precise than NSPA in theory, its implementation is restricted by significant computational expenses and the difficulty in choosing suitable ground motion records [4].

Recent research has focused on comparing the accuracy of NSPA and NTHA in predicting the nonlinear behaviour of building structures under seismic loads. Studies have shown that NSPA can be a useful tool for estimating the seismic response demand and identifying weak structural elements in building structures. However, it has also been noted that NSPA is an approximation method that lacks a rigorous theoretical foundation and that its accuracy can be affected by a variety of factors, such as the assumptions made in modelling the building structure and the selection of the pushover curve[12]–[14].

On the other hand, NTHA has been found to be a more accurate method for predicting the nonlinear behaviour of building structures under seismic loads. However, its practical application is limited due to its high computational cost and the challenge of selecting appropriate ground motion records [15]. Despite these limitations, NTHA remains an important tool for assessing the seismic performance of building structures and has been used in a variety of research studies to investigate the behaviour of specific building structures under different seismic loads.

Overall, the literature suggests that both NSPA and NTHA have their advantages and limitations and that the selection of the appropriate method depends on the specific needs of the analysis [15], [16]. While NSPA can be a useful tool for estimating the seismic response demand and identifying weak structural elements in building structures, NTHA is a more accurate method for predicting the nonlinear behaviour of building structures under seismic loads. Further research is needed to improve the accuracy and practicality of both methods and to identify ways to combine the strengths of both methods for improved seismic design of building structures.

3. Methodology

The methodology of this study involves the use of two different analysis methods to evaluate the nonlinear behaviour of 3- and 5-storey reinforced concrete building models under seismic loads as shown in Figure 2.

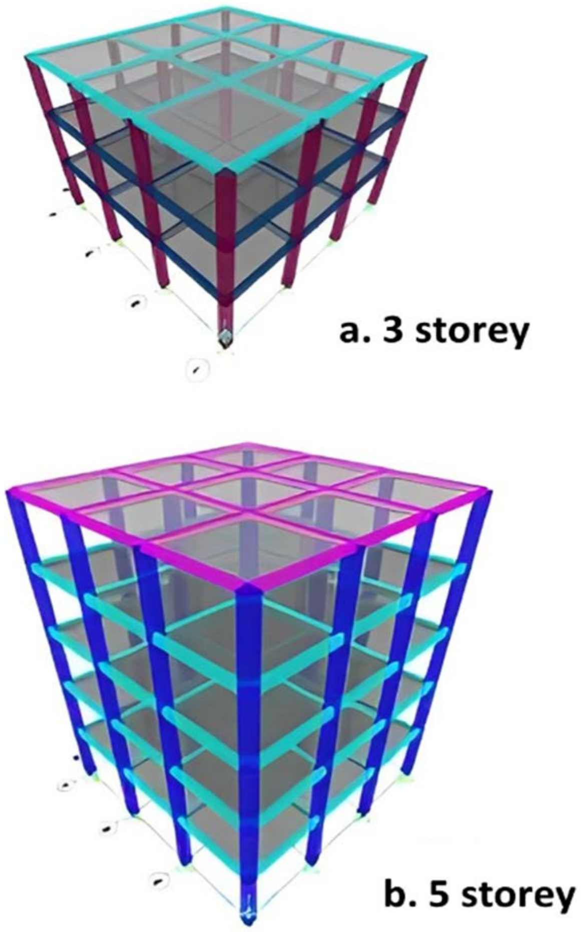


Figure 2. The 3D model from SAP2000

The compressive strength of the concrete was taken to be 30 MPa and the yield strength of the rebar was taken as 420 MPa. For the ultimate design load, 6 kN/m^2 was considered, which includes factored dead and live load combinations. The building was designed to withstand moderate seismic activity in accordance with Indonesian Building Code SNI 1726-2019[17] and SNI 2847-2019[18]. The seismic design parameters are presented in Table 1.

Both NSPA and NTHA will be performed using the SAP2000 software [19], which is a widely used software for structural analysis. To model the nonlinear behaviour of the reinforced concrete frame elements in the building, the nonlinear frame hinge element will be used. The frame hinge element accounts for the flexural and shear behaviour of the beam-column joint and allows for accurate modelling of the plastic hinges.

For NSPA, the building model will be subjected to a series of incremental lateral load patterns applied at each floor level, and the lateral force versus lateral displacement curve will be generated. The maximum lateral displacement at each floor will be used to calculate the inter-story drift ratios.

For NTHA, the building model will be subjected to the selected ground motion records, and the response of the building will be calculated based on the time history analysis. The inter-storey drift ratios and plastic hinge distribution will be obtained from the analysis results.

It is worth noting that NTHA involves selecting several ground motions based on earthquake characteristics such as magnitude, fault distance to the earthquake's centre, and soil classification. Figure 3 shows the modified response spectrum used in NTHA.

Table 1. Seismic parameters

Parameters	Value (medium soil)
S_S (g)	1.129
S_1 (g)	0.508
F_A	1.048
F_V	1.5
S_{MS} (g)	1.184
S_{M1} (g)	0.763
S_{DS} (g)	0.789
S_{D1} (g)	0.508

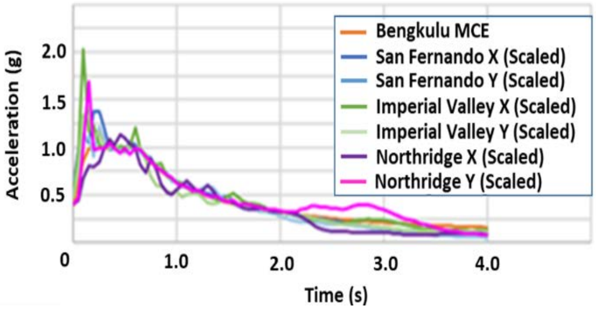


Figure 3. Modified response spectrum

Generally, the performance limit can be categorized into two groups: (1) global/structural limits and (2) local/element limits. The performance limits are evaluated in accordance with the ATC-40[20]. For the global limits, the structural performance is tied to the inter-storey drift ratio as shown in Table 2. On the other hand, the local limits are determined based on the plastic hinge rotation capacities.

Table 2. Drift ratio limit for global performance

Immediate Occupancy (IO)	Damage Control	Life Safety (LS)	Structural stability
0.01	0.01-0.02	0.02	0.33 Vi/Pi

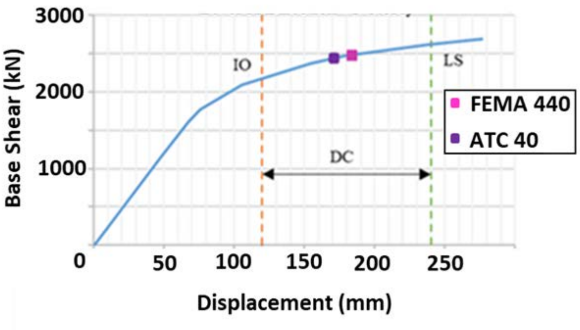
The results of NSPA and NTHA will be compared based on the inter-story drift ratios and plastic hinge distribution. The accuracy of NSPA in predicting the nonlinear behaviour of the building structure under seismic loads will be evaluated by comparing it to the more rigorous and accurate NTHA.

The results of the study will provide important insights into the applicability and limitations of NSPA and the nonlinear frame hinge element for the seismic design of building structures.

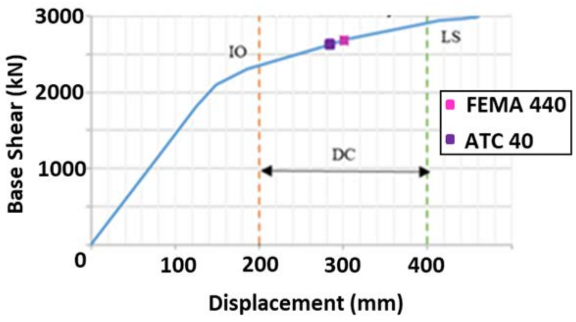
4. Results and Discussion

4.1. NSPA Results

Through pushover analysis, a capacity curve is generated to depict the relationship between the base shear and the top lateral displacement of a building. The capacity curve can be used to assess the seismic performance of a building, by comparing it to the demand curve that represents the expected seismic forces during an earthquake. The capacity curves obtained from pushover analysis are presented in Figure 4.



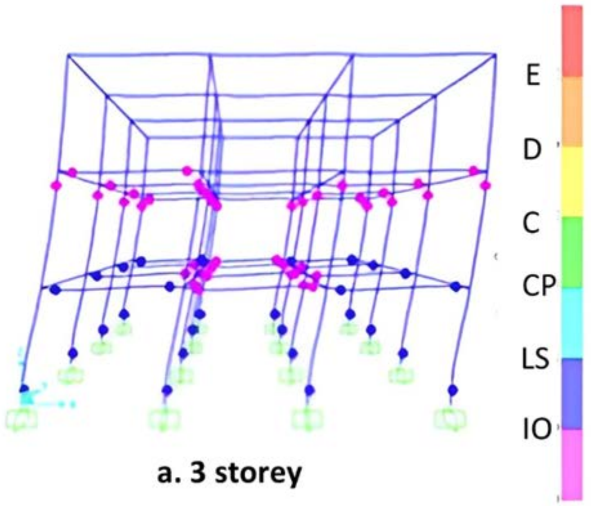
a. 3 storey



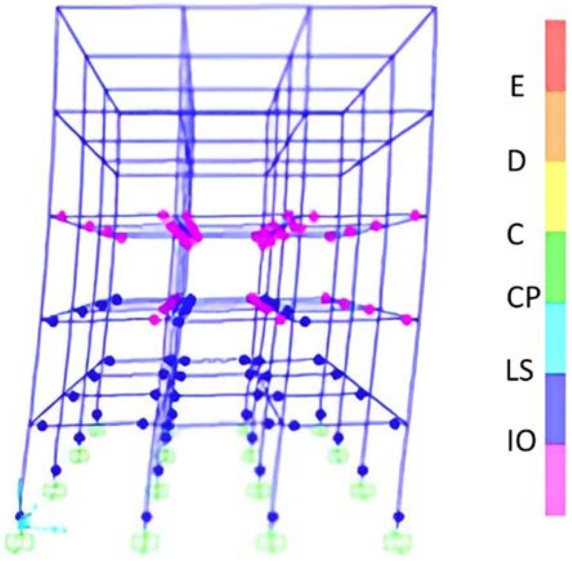
b. 5 storey

Figure 4. Capacity curves generated from pushover analysis

It can be seen that the drift ratio falls between 0.01 and 0.02, indicating a global performance level of Damage Control (DC) for the 3- and 5-storey buildings analysed. The local performance level, on the other hand, can be determined by identifying the worst deformation resulting from the appearance of plastic hinges at the performance point during the analysis. Figure 5 shows the plastic hinge formation at the performance point for 3- and 5- storey buildings.



a. 3 storey



b. 5 storey

Figure 5. Plastic hinge development at performance point

4.2. NTHA Results

Nonlinear time history analysis is performed for each ground motion, resulting in time-varying displacement and base shear data. The maximum displacement and base shear values obtained from the analysis of each ground motion are presented in Table 3.

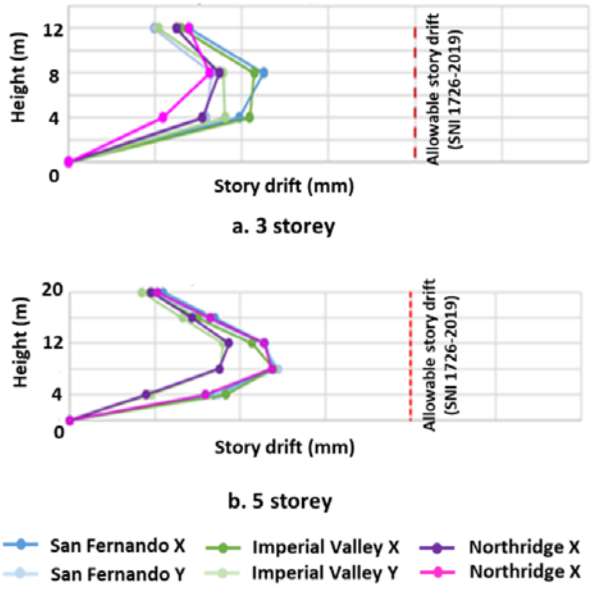
The maximum displacement represents the maximum displacement of the structure during the time history of the ground motion, while the base shear is the maximum force that the foundation of the structure is subjected to during the ground motion. These values are important in assessing the seismic performance of the structure and can be used to compare the response of the structure to different ground motions or to evaluate the adequacy of the structure's design.

Table 3. Maximum Displacement and Maximum Base Shear obtained from NTHA

Earthquake Event	3-Storey Building			
	Roof Displacement (mm)		Base Shear (kN)	
	T	Value	T	Value
San Fernando X	9.55	224.64	3.47	2647.9
San Fernando Y	3.52	168.85	12.09	2413.48
Imperial Valley X	13.035	221.23	9.94	2579.89
Imperial Valley Y	15.47	185.07	15.445	2339.94
Northridge X	19.18	181.2	21.24	2277.51
Northridge Y	19.52	164.19	23.94	2451.42
Earthquake Event	**5-Storey Building**			
	Roof Displacement (mm)		**Base Shear (kN)**	
	T	**Value**	**T**	**Value**
San Fernando X	3.66	366.4	9.25	2769.35
San Fernando Y	3.81	361.01	9.75	2678.94
Imperial Valley X	29.145	351.8	10.76	2936.97
Imperial Valley Y	9.45	267.23	10.205	2736.3
Northridge X	17.32	275.84	16.54	2660.23
Northridge Y	15.72	356.34	19.86	2594.75

The global acceptance criteria involve checking the story drift caused by each analysed earthquake event. The parameters used to guide the fulfilment of the global acceptance criteria are the roof displacement and the period of the largest roof displacement (T), as listed in Table 2. T is used as a reference to determine the displacement value on the lower floors, and the story drift is then calculated by subtracting the displacement of the lower floor from that of the upper floor. The story drift of each earthquake event is compared with the allowable limit specified in SNI 1726:2019[12]. The outputs of the story drift after being compared with the allowable limit are presented in Figure 6.

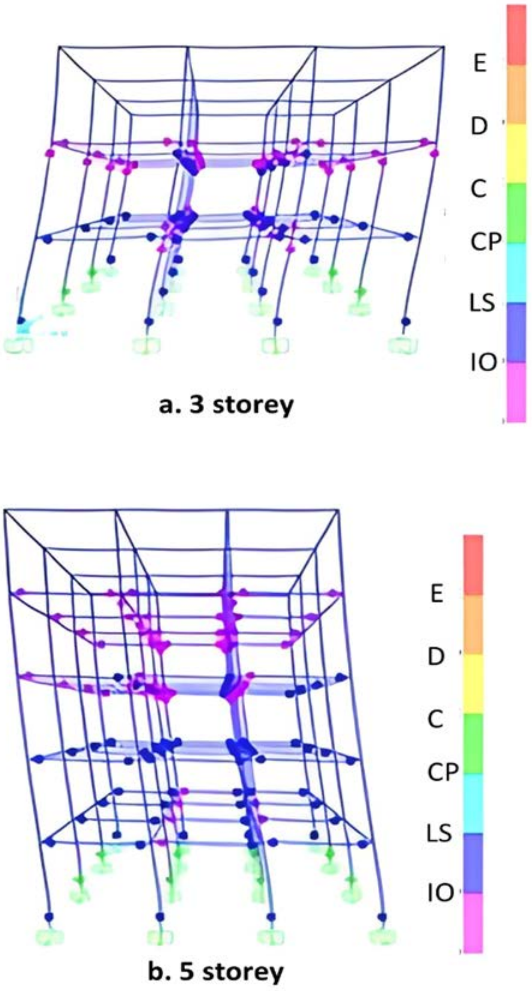
The maximum deformation of the plastic hinges' appearance during the last step or interval of each analysed earthquake event can be used to determine the local performance levels. Development of the plastic hinge deformations in a 3- and 5-story building are shown in Figure 7.



a. 3 storey

b. 5 storey

Figure 6. Global acceptance criteria



a. 3 storey

b. 5 storey

Figure 7. Plastic hinge development obtained from NTHA

4.3. NSPA vs NTHA

Table 4 compares the global and local performance levels obtained from both nonlinear static pushover analysis and time history analysis for both directions (X and Y).

Table 4. Global performance comparison

Earthquake Event		**Global performance**	
		3-storey	**5-storey**
Static Pushover	X	Damage Control (DC)	Damage Control (DC)
	Y	Damage Control (DC)	Damage Control (DC)
Dynamic Time History	X	Limited Safety (LS-CP)	Limited Safety (LS-CP)
	Y	Damage Control (DC)	Limited Safety (LS-CP)

When comparing the global performance level of the two analyses, the performance level for non-linear static pushover analysis is determined by the ratio between the displacement target and the building height based on the performance point of the FEMA 440 [21] approach. This is because performance points using the FEMA 440[16] approach produce larger and more conservative displacement parameters, which will have a more negative impact on the ratio value used to determine the global performance level [3].

Meanwhile, the performance level for non-linear dynamic time history analysis is determined by the largest story drift ratio value among the three pairs of earthquake events and compared to the acceptance criteria. For the X-directional earthquake event, the largest story drift ratio in the 3-storey and 5-storey buildings was 2.2% and 2.4%, respectively, which corresponds to the Limited Safety (LS-CP) level. For the Y-directional earthquake event, the largest story drift ratio in the 3-storey and 5-storey buildings was 1.8% and 2.4%, respectively, which correspond to the Damage Control (DC) and Limited Safety (LS-CP) levels.

When comparing the local performance levels of the two analyses, for pushover analysis, the worst deformation condition should be taken during the performance point step. On the other hand, for time history analysis in 3- and 5-storey buildings, the worst deformation condition of the plastic hinge formation was determined based on the three pairs of earthquake events. As shown in Table 5, for direction X, the San Fernando earthquake caused the worst conditions in both 3- and 5-storey buildings. As for direction Y, the worst conditions in the 3-storey building were caused by the Imperial Valley earthquake, and in the 5-storey buildings, they were caused by the San Fernando and Northridge earthquakes due to their similar final conditions.

Table 5. Local performance comparison

Earthquake Event	**3-Storey Building**			
	Local Performance Level			
	Element	**Hinge Formed**	**Condition**	
Pushover X	B1	8	IO-LS	🟦
	B2	0	< IO	⬜
	K1	20	IO	🟪
Pushover Y	B1	8	IO-LS	🟦
	B2	0	< IO	⬜
	K1	24	IO	🟪
NTHA X (E-W)	B1	12	IO-LS	🟦
	B2	12	IO	🟪
	K1	2	CP	🟩
NTHA Y (N-S)	B1	8	IO-LS	🟦
	B2	0	< IO	⬜
	K1	14	IO	🟪
Earthquake Event	**5-Storey Building**			
	Local Performance Level			
	Element	**Hinge Formed**	**Condition**	
Pushover X	B1	24	IO-LS	🟦
	B2	0	<IO	⬜
	K1	8	IO	🟪
Pushover Y	B1	20	IO-LS	🟦
	B2	0	<IO	⬜
	K1	0	<IO	🟪
NTHA X (E-W)	B1	36	IO-LS	🟦
	B2	0	<IO	🟪
	K1	8	IO	🟩
NTHA Y (N-S)	B1	36	IO-LS	🟦
	B2	0	<IO	⬜
	K1	16	IO	🟪

For both the global and local performance levels, it can be said that time history analysis is a more rational analytical method for evaluating building structures under earthquake behaviour. Time history analysis was chosen because it is a more detailed analysis method that uses the original ground motion earthquake load, and the resulting outputs vary over the interval duration of the earthquake. This is supported by the worse global and local performance levels produced by the time history analysis, as shown in Table 4 and Table 5. However, as a preventive measure, designers should take more conservative steps. In this study, pushover analysis was not as reliable as time history analysis because it is a very simple method that produces only a performance point and is less conservative in terms of the resulting performance level.

5. Conclusions

This study provides information about the evaluation of the seismic performance of buildings through two different analytical methods, nonlinear static pushover analysis and nonlinear dynamic time history analysis. Pushover analysis generates a capacity curve that can be used to assess the seismic performance of a building, while time history analysis is a more detailed analysis method that uses original ground motion earthquake load and results in time-varying displacement and base shear data. The maximum displacement and base shear values obtained from time history analysis are important in assessing the seismic performance of the structure and can be used to compare the response of the structure to different ground motions or to evaluate the adequacy of the structure's design.

The global and local performance levels of the building structures are determined using acceptance criteria set by relevant standards.

The comparison of global and local performance levels between the two analyses indicates that time history analysis is a more rational approach for assessing building structures under earthquake behaviour. However, as a precautionary measure, designers should take more cautious steps. On the other hand, pushover analysis produces less reliable performance levels than time history analysis.

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